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IMPROVED Cl ION CAPTURE BY ACOUSTICALLY ENHANCED DRY CaO SCRUBBING

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ABSTRACT

An entrained flow reactor was constructed to conduct the CaO/HCl reaction in an acoustic field of 160 dB in an attempt to increase the extent of reaction by removing gas-film limitation. Several reaction parameters were examined. Three mass mean particle size fractions (4, 56 and 91μm) and three reaction temperatures (125, 200 and 350°C) were investigated.

Results show that reaction conversion increased 86% at 200°C and 50% at 350°C for the 56 μm mass mean diameter fraction at reaction times less than 1 s. Conversion for the 91 μm mass mean diameter fraction did not change at any temperature. The 4 μm mass mean diameter fraction did not show any statistically significant reaction conversion improvement in an acoustic field. Mercury porosimetry results for the smallest CaO fraction exhibited a decrease in particle porosity indicating the onset of product layer diffusion control. The reaction conversion improvement in a resonant acoustic field was found to be due to additional particle residence time in the reactor.

INTRODUCTION

Gas-solid reactions are important to industry and find application in areas such as catalysis and air pollution control technology [1-3]. Many gas - solid reactions can be described by the unreacted-core model.[4-8] Extent of reaction of gas - solid reactions following the unreacted-core model can be limited by either gas -phase mass transfer control, chemical reaction control or product layer diffusion (PLD) control depending on parameters such as particle size, reaction temperature and reactant gas concentration. The reaction might experience one or a combination of these rate-limiting steps. It is common for one type of limitation to be in

operation at the onset of the reaction with reaction limitation changing with time. Any measure taken to reduce or eliminate the mass transfer limitations will allow the reaction to run to a higher level of conversion in a finite time.

Experimental data for the reaction of calcium sorbents and acidic gases fits well with the unreacted-core model[8]. The parameters most responsible for limiting the gas-solid reaction are sorbent particle size, specific surface area and porosity. According to reaction modeling and experimental results, the reaction cycles through an initial time of chemical control, followed by diffusion control through the product layer. At reaction initiation, the reactant gas diffuses throughout the particle as far as it can penetrate. Penetration is limited by a balance of porosity and particle size as the reaction progresses. As previous experimental results indicate, smaller particles experience greater conversion because reactant gas can more uniformly penetrate the whole particle. As the particle size increases, the reaction proceeds before the reactant gas has penetrated completely throughout the interior of the particle. As the reaction proceeds, limestone sorbent porosity is reduced due to the greater molar volume of the reaction product versus the reactant solid. In this manner, the product layer develops around the surface of the particle and PLD control begins.

Several chemical, physical and combustion processes[9-21] are known to benefit from oscillating flows induced by pulse combustors or external sound generators if the SPL is greater than an experimentally determined threshold. Improved reaction conversion is thought to result from enhancement of transport processes. It has been shown numerically that a differential gas and solid phase velocity or slip velocity exists for solid particles sufficiently large to avoid entrainment in the gas phase[18]. A correlation exists between reaction improvement and the solid particle slip velocity which develops greater heat and mass transfer coefficients for calcination and coal combustion. Yavuzkurt et al[19, 20] examined the effects of acoustics on coal combustion and found combustion to improve due to improved heat transfer to the particle. Improved heat and mass transfer was demonstrated through heat and mass transfer coefficients 45-82% greater than without acoustics.

Investigation of the CaO/HCl reaction has been conducted in differential reactors to minimize gas-film limitations in order to focus experiments to determine intrinsic rate constants and solid diffusivities in the product layer diffusion regime[24-26]. In reality, gas-film diffusion is present for short contact time reactions. The gas-film limitation is strongest for small particles at the onset of reaction. In general, dry scrubbing occurs in an entrained flow type configuration with short contact times with sorbents less than 10 μm, thus making the reaction a prime candidate for gas-film diffusion limitation. Although wet scrubbing technology removes more acidic components from the flue gas, dry scrubbing has the advantage of generating a dry product, simple process design, and little pressure drop through the reaction vessel. Hence, if dry scrubbing acidic gas removal efficiency can be improved, then the benefits of dry scrubbing can be realized. Improvement of the gas-film limitation may improve the viability of dry scrubbing of acidic gases.

Acoustics is proposed for improving the CaO/HCl gas-solid reaction. Rather than increase the flow velocity through the reaction system to overcome gas-film transfer limitation as in a differential reactor, acoustic slip velocity might improve the concentration gradient of reactant gas in the particle boundary layer. A commercial scale differential reactor would require more energy for generating higher flue gas flow rates and would increase pressure drop in the reaction vessel.

An entrained flow reactor was designed and constructed in order to study the CaO/HCl reaction in an environment in which it would have direct applicability to modern dry scrubbing. A common method of conducting dry scrubbing is to react the sorbent with the acidic gas by injecting the sorbent directly into the flue gas stream[22,23]. The difference between dry scrubbing systems lies not in the configuration as much as in the injection point for the sorbent. A limestone sorbent can be injected in a post combustion zone or a $Ca(OH)_2$ sorbent can be injected after heat recovery where the flue gas temperature is less than 300°C. An entrained flow reaction investigation involving short contact times with temperatures below 300°C was be pursued for this work.

In this investigation we were interested in a specific example of a type of reaction associated with dry scrubbers. The CaO/HCl reaction was of interest due to recent efforts to characterize kinetics, temperature and particle size effects of the reaction[24-27]. The reaction proceeds as follows:

$$2HCl(g) + CaO(s) \longrightarrow CaCl_2(s) + H_2O(g) \qquad (1)$$

EXPERIMENTAL

Materials

Calcium oxide of 96.2% purity and hydrogen chloride gas were the two primary reagents used in this study. Calcium oxide pellets were ground and sifted to generate the desired size fractions. Mass mean CaO particle diameter was determined by a sedimentation method using a Micromeritics Sedigraph 5100 and surface area according to the BET technique. Pore volume was determined using a Micromeritics AutoPore III 9420, a mercury intrusion technique. Pore size distribution is calculated with the Washburn equation for the pressure difference across a curved liquid surface.

The three CaO fractions used in this study will be referred to as the Large, Medium and Small fractions. Table 1 lists the fraction name, mass mean particle size and distribution range for each fraction. The distribution range indicates the particle size range consisting of 80% of the particle mass of a particular CaO fraction. The remaining 20% of mass is below the lowest particle size in the distribution range given in Table 1. The size distribution is given as an illustration of the composition of the CaO fractions.

Specific surface area of the three fractions does not change with particle size. This result is in agreement with other investigations where surface area changed only with limestone geologic type and pore structure[28]. Furthermore, the values obtained for surface area in Table 1 are in agreement with those determined in other studies where specific surface area was 11-13 m^2/g[25,26].

The pore volume measurements from Table 1 are an important factor which will affect the extent of reaction achieved in EFR experiments. The recent work performed with the CaO/HCl

reaction does not account for pore volume differences of the sorbent. However, Borgwardt[28] showed that different calcines have different pore volumes and pore sizes which will affect the extent of reaction and when the reaction will become product layer diffusion controlled. The measured values for pore volume in Table 1 compare to the type 1 sorbent used by Borgwardt[28]. This smallest pore diameter calcine was shown to plug quickly with reaction product and cause the reaction to be rapidly PLD controlled. Hence, the pore diameter will be important to interpretation of extent of reaction data.

Composition of the reaction product was accomplished by measuring the concentration of calcium and chloride ions by Atomic absorption spectroscopy and with an ion selective electrode, respectively. The extent of reaction is expressed as fractional conversion of the CaO sorbent. The fractional conversion, X_{CaO}, is the fraction of solid reactant converted to product and is expressed in the following relation.[29]

$$X_{CaO} = \frac{mmol.CaO_i - mmol.CaO_f}{mmol.CaO_i} \qquad (2)$$

where mmol is millimoles of initial and final CaO.

Entrained Flow Reactor

The EFR consists of a quartz glass reactor, a sorbent feeder, ammonia reaction quench, a computer interfaced data acquisition system and reaction product collection screen. Figure 1 shows a schematic of the major reactor components. Nitrogen carrier gas was preheated by an electric gas circulation heater which was introduced at the top of the reactor. Reaction temperature was maintained by three zones of electrical resistance radiant heaters controlled independently by temperature controllers. CaO sorbent was injected into the carrier gas at the top of the reactor where it traveled through a 24 inch injection tube to achieve reactor temperature before contact with the gaseous reagent. The gas-solid reactants were quenched rapidly by an injection of NH_3 gas at the bottom section of the reactor called the decoupler. The reaction product was collected in the decoupler and in the collection cylinder. Both the acoustic and reactor sections are 1.5 meters

long. A portion of the reactor was fitted with a series of quartz optical viewports for entry of a laser beam for conducting gas and particle velocity measurements. Thermocouple and pressure transducer ports were mounted on the vertical tube section for collecting temperature and sound pressure data.

This EFR differs from conventional entrained flow reactors because this reactor is fitted with compression drivers which are attached on the tube walls to generate an intense resonant sound wave within the reactor tube. Additionally, the decoupler at the bottom of the reactor section dampens the sound pressure oscillations from the carrier gas in addition to providing the necessary retention time to quench any unreacted HCl. The entire reactor tube was encased in a steel shell to channel leaks to the exhaust hoods to prevent gas leaks from invading the surrounding environment.

A fluidized bed sorbent feeder was used to inject the desired quantity of CaO into the reactor. The sorbent feeder was operated in batch mode to obtain approximate residence time data for steady flow experiments by incorporating laser diodes mounted at the bottom of the sorbent injection tube and at the top of the decoupler. The time difference between injection of CaO at the top of the reactor to the bottom of the reactor section was determined from the signal display on a digital oscilloscope. The sorbent feeder was operated in a continuous mode for the reaction conversion experiments in both steady flow and with acoustics.

The experiments in the EFR were conducted with concentration of HCl at 614 ppm and over the temperature range 125-350°C with each of the three CaO fractions previously described. Each experiment was run continuously for approximately 15 minutes. Unless otherwise noted, space-time of the experiments was 0.68s.

EXPERIMENTAL RESULTS

A series of experiments of various CaO size fractions and reactor temperatures was run to establish a baseline for comparison of reaction in an intense acoustic field. Figure 2 illustrates the behavior of reaction conversion with CaO size fraction, reactor temperature for the case of no sound pressure. Reaction conversion expressed as fractional conversion of CaO is shown over a range of reactor temperature.

Conversion is observed to increase with decreasing CaO particle size and slightly increase with reactor temperature. The Large CaO fraction exhibits little change in conversion with reactor temperature. The Medium CaO fraction does show an increase in reaction conversion with increasing temperature, with a maximum average conversion of 5% at 350°C. The Small fraction does not significantly change with temperature in this range. The higher conversion for smaller CaO particles is likely due to the greater degree of interior reaction in the smaller particles compared to the larger particle fractions. The importance of the internal reaction plays a greater role as particle size decreases[28]. These results are supported by other investigators who have reported reaction conversion of CaO and HCl to increase with increasing temperature and decreasing CaO particle size[24-27].

With a baseline established over a temperature and particle size range, a series of experiments were conducted at 163 dB to determine the effect of sound pressure on reaction conversion. Figures 3 to 5 illustrate the conversion results expressed as fractional conversion of CaO for the Large, Medium and Small CaO fractions over the temperature range 125 to 350°C. The 163 dB results are compared to the baseline results of Figure 2.

Figure 3 shows that reaction conversion in an acoustic field for the Large CaO fraction did not change from the baseline values established in Figure 2. The acoustic field had little effect on the reaction. The large particle size does not experience the same degree of reactant gas penetration as does a smaller particle, thus limiting its extent of conversion. However, for the Medium CaO fraction in Figure 4, while no change in reaction conversion is evident at 125°C, an appreciable increase has occurred at 200°C and 350°C as more of the interior of the particle was accessible by HCl.

Figure 5 shows the conversion results for the Small CaO fraction under similar reactor conditions and SPL as described for the Large and Medium CaO fractions. A slight improvement in reaction conversion is realized only at 200°C and 350°C. The reaction conversion levels at each temperature with acoustics is similar, indicating that conversion plateaus for the small CaO particles under the present reaction conditions for residence time and

temperature. It is likely that conversion for the Small CaO fraction is maximized due to a decrease in reaction product porosity. The molar volume of $CaCl_2$ is three times that of CaO[26]. As reaction proceeds, the porosity is reduced[26].

Pore volume measurement for a sample of product from a Small fraction experiment is compared to an unreacted sample in Table 2. The total intrusion volume, a direct measurement, is reduced after reaction at 200°C, indicating that the solid has begun to become plugged with reaction product. The calculated pore area reflects the change in reaction sites available for reaction. As the reaction proceeds, accessibility of reactant gas to reaction sites on the solid becomes hindered, limiting further reaction. Since the present experiments are below sintering temperature of the CaO particles, pore volume reduction results from reaction progression as more $CaCl_2$ is formed.

DISCUSSION

The fractional conversion was improved for the Medium fraction, but not significantly for the Large and Small sorbent fractions. Several factors might be responsible for the observed experimental results. Previously, gas-solid reactions and the limitations they might experience were discussed, so the CaO/HCl reaction will be examined from the viewpoint of gas-film and kinetic limitations. The time scale of the reaction for the EFR is short and large levels of conversion leading to PLD control were not developed for the Medium fraction. The effects of particle size, sound pressure level, turbulence and pore structure will be examined to determine whether gas-film or chemical control limitations are in operation and overcome to account for the improvement in conversion for the Medium sorbent fraction.

Gas-Film Diffusion Control

Reaction conversion may be limited by gas-film diffusion control. Previous work conducted calcium sorbent and acidic gas reactions in differential reactors. The gas concentration in a differential reactor was kept at a sufficient level so adequate reactant gas concentration was always present. Gas-film diffusion resistance was minimized by increasing the carrier/reactant gas velocity in the reactor so the gas concentration around the fixed bed of solid reactant particles was replenished quickly. However, an entrained

flow reaction might be limited by gas-film diffusion if the gas concentration is low and the reaction depletes the reactant gas around the sorbent particles. In this case the turbulent, oscillating flow resulting from a resonant acoustic field might improve the reactant gas concentration around the boundary layer of the solid particle. The theory to acoustic improvement of boundary layer concentration of reactant gas is described by an entrainment factor and slip velocity[30].

The entrainment of a solid particle in an acoustic field is described by an entrainment factor, η_e. The entrainment factor is defined as the ratio of the maximum particle velocity to the maximum gas velocity. The entrainment factor is found by equating the particle drag and inertial forces for a smooth sphere[30]. The entrainment factor is given by equation 3,

$$\eta_e = \frac{v_{p,max}}{v_{g,max}} = \frac{1}{(1+\omega^2\tau_p^2)^{1/2}} \qquad (3)$$

where the particle and gas velocities are defined as

$$v_p = v_{p,max}\sin\omega t \qquad (4)$$

$$v_g = v_{g,max}\sin(\omega t-\phi) \qquad (5)$$

respectively and τ_p represents the particle relaxation time given as,

$$\tau_p = \frac{\rho_p D^2}{18\mu_g} \qquad (6)$$

where ρ_p is the particle density, μ_g the gas viscosity, ω the frequency of the acoustic wave, ϕ the phase difference between the particle and gas motion, D the particle diameter and t is the time.

A plot of entrainment factor versus particle diameter can be generated for the CaO/HCl system as given in Figure 6. From this plot it is seen that full entrainment corresponds to $\eta_e=1$ and $\eta_e=0$

no entrainment. By increasing frequency of sound or increasing the particle diameter the entrainment of particles is minimized. A slip velocity develops for particles that are not entrained in the flow. The less entrained a particle is in the flow, the greater the slip velocity between the solid and gas phases. The mass mean particle diameters for the Large and Medium fractions have a low entrainment factor according to Figure 6. Since the solid particle has a low entrainment in the gas phase, a slip velocity is created over the particles that may improve reactant gas concentration around the CaO particles.

Experiments were conducted to verify whether gas-film diffusion limitations were present and if the differential gas/solid velocity would overcome the gas-film limitation to reaction. This was accomplished by experimenting with different sound pressure levels and measuring turbulence intensity with the LDV system and comparing the CaO conversion among the experimental conditions tested. The turbulence of the resonant sound wave may be supplying the necessary mixing to improve gas-film transfer limitation.

Previous investigations reported values of 140 to 160 dB necessary to achieve improvements in various reaction systems[9,10]. For this work, two additional levels of SPL were chosen, 140 dB and 150 dB. Table 3 shows the reaction conversion for the Medium CaO fraction at 200°C.

The data suggests that a threshold sound pressure level exists at 160 dB at 200 °C. No conversion changes are evident at 140 dB or 150 dB as compared to the base case conversion. However, conversion increases for sound pressure level above 160 dB. Perhaps some characteristic of the flow field which results from acoustics is affecting the CaO conversion. The turbulence intensity was examined to see if a correlation exists linking the turbulence of the sound wave and the conversion improvement observed. In order to examine the flow field of the reactor section, LDV was used to measure turbulence intensity at the three sound pressure levels of Table 3.

Turbulence intensity is defined as[31]

$$I \equiv \frac{(1/3\overline{u_i u_i})^{1/2}}{U_o} \qquad (7)$$

where u is the component velocity and U_o the mean flow velocity. Turbulence intensity can be defined for each velocity component as the root mean square referenced to a mean flow velocity.

Turbulence intensity levels measured by laser doppler velocimetry for the downward flow component show that turbulence intensity increases at 140 dB SPL according to turbulence intensity measurements provided in Table 4.

According to Tables 3 and 4 no conversion improvement is evident at 140 or 150 dB though turbulence was increased at 140 and 150 dB. This indicates that turbulence intensity is not directly related to conversion improvement. The 160 dB SPL threshold for conversion improvement is not explained by turbulence intensity. This demonstrates that no gas-film mass transfer improvement is evident for the CaO/HCl reaction, though entrainment factor calculations demonstrate conditions conducive to developing a slip velocity around the solid particles.

Since the sorbent particles of the Large fraction have the smallest entrainment factor and thus the largest slip velocity, mass transfer improvement through the gas-film layer should be improved under these conditions. The acoustic field should have the greatest affect on the Large fraction compared to the smaller two fractions tested since the Large fraction is least entrained in the reactor flow. The large difference in relative velocity between the solid and gas phases should improve the concentration gradient around the sorbent particles, improving extent of reaction. However, the experiments run with the Large fraction in Figure 3 showed no significant conversion improvement. Since gas-film mass transfer is not limiting the reaction, another factor must be affecting the converion enhancement.

Chemical Control

Reaction limitation by chemical control has no mass transfer limitations and reaction conversion can only be altered through

reaction time and temperature. Equations 8 - 11[29] were used to generate predictive curves to estimate the reaction limiting mechanism using a rate constant and diffusion coefficient from Duo et al[8] and the measured values of CaO density, grain size and HCl concentration from the present work. A range of extents of conversion was calculated with respect to reaction time. Figure 7 shows the fractional conversion with reaction time for both chemical kinetic control and PLD control.

$$\frac{t}{\tau_r} = 1-(1-X_B)^{1/3} \qquad (8)$$

where X_B is the measured value of conversion of the solid reactant and τ_r is the time for complete conversion of the solid reactant and is given by the following expression[29],

$$\tau_r = \frac{\rho_B R_p}{b k_s C_{Ag}} \qquad (9)$$

where ρ_B is the molar density of the solid, R_p the radius of the grain, b the stoichiometric coefficient, k_s the intrinsic rate constant ($k_s = 1\text{x}10^{-4}$ m/s from the literature[8]) and C_{Ag} the concentration of reactant gas. The radius of a grain of a CaO particle is estimated through the following relation, $R_p = 3/\rho_B S$ where S is the surface area of the calcine.

For a reaction under PLD limitation the rate expression is[29],

$$\frac{t}{\tau_r} = 1-3(1-X_B)^{2/3}+2(1-X_B) \qquad (10)$$

and τ_r is given as[29],

$$\tau_r = \frac{\rho_B R_p^2}{6bD_e C_{As}} \qquad (11)$$

where D_e is the solid diffusion coefficient for the reaction using a value of $D_s = 1x10^{-13}$ m^2/s from the literature[8].

The predictive curves show initial kinetic control for the CaO/HCl reaction using the sorbent and gas property data determined for the present study and k_s and D_e from another CaO/HCl investigation. After about 60 s reaction limitation shifts from kinetic control to PLD control. As the reaction proceeds a product layer builds around the particle surface, hindering subsequent reaction progress. PLD control becomes more limiting as reaction time increases.

Space-time of the present experiments is 0.68 s where space-time is defined as the volumetric flowrate divided by the reactor volume. This means that 0.68 s is required for the reactor volume to change. Since space-time is 0.68 s, the conversion data gathered falls under the regime of chemical kinetic control according to Figure 7. Chemical conversion for reactions under chemical control is changed by either altering residence time or reaction temperature. The experiments run with acoustics at 200°C for the Medium fraction demonstrate an improvement in reaction conversion as shown in Figure 4. The greater reaction conversion must have occurred through additional reaction time or temperature. The reactor is run isothermally and the CaO particles reach the reactor temperature in only 173 ms assuming that the particles do not heat up in the sorbent injection tube. Hence, conversion enhancement likely occurs through additional reaction time. An experiment was devised to test whether reaction time was affected by acoustics.

An experiment with a shorter reaction zone was run to compare the conversion results of the shorter zone using acoustics to the conversion achieved with a longer reaction zone without acoustics. The shorter reaction zone was created by extending the sorbent injection tube an additional 12 inches into the reactor. Table 5 presents the results of the experiments conducted with two different reaction zone lengths.

Similar reaction conversions are obtained by comparing the short reaction length with acoustics to the long reaction length without acoustics. This evidence shows by using acoustics, a similar

conversion can be obtained in a shorter reaction length. Hence, less space-time is required to achieve a desired level of reaction conversion if acoustics are used.

The result that acoustics can increase the particle residence time is corroborated by the work of Sujith[32] who examined the affect of longitudinal waves on the evaporation of droplets of water and methanol in an acoustic field over 160 dB. Sujith[32] numerically determined that the terminal velocity of the droplets was decreased due to the acoustic field. A decreased terminal velocity would increase the residence time of the droplet in the reactor.

The improved extent of reaction for the CaO/HCl reaction is demonstrated to occur through additional reaction time by comparing differing space-time in Table 5. It should hold that conversion for the reaction using acoustics should fall on a conversion versus reaction time plot for chemical reaction control. Figure 8 shows conversion at 200°C for the Medium fraction expressed from equations 8 and 9 and particle residence time determined from laser diode measurements in the reactor section. The particle residence time is not a true reaction residence time since it is not determined during the continuously run experiment. However, the residence time determination of a plug of sorbent particles indicates the increased levels of residence time. The conversion resulting from experiments with and without acoustics fall close together on the same conversion lines indicating that acoustics increases residence time of the particles in the reactor.

SUMMARY AND RECOMMENDATION

The entrained flow reactor operating without acoustics produces results similar in trend, but different in magnitude to those obtained using fluidized bed systems. The results without acoustics show that conversion increases with increasing reactor temperature and decreasing particle size.

Acoustics was used to improve the extent of conversion over those obtained without acoustics. No significant improvement in reaction conversion was observed for the Large fraction or Small sorbent fraction at any temperature. However, the Medium fraction experienced conversion improvements of 85 % at 200°C and 50 % at 350°C. Significance was found at the 95 % confidence

level according to a t-test comparison of the conversion mean with and without acoustics.

A conversion improvement was expected to be due to mass transfer improvement around the boundary layer of the sorbent particle, called gas-film diffusion control. Turbulence intensity measurements in an acoustic field were found to be over 25 % compared to 3 % without acoustics. No correlation between turbulence intensity and reaction conversion improvement with acoustics was found. However, predictive kinetic curves illustrating chemical control and PLD control showed that the 0.68 s time frame of the EFR experiments was in a chemical control region. Thus, time or temperature should be responsible for the observed conversion enhancement in an acoustic field. Experiments with a 12 inch shorter reaction zone using 160 dB SPL showed conversion to be similar to the longer reaction zone without acoustics indicating particle residence time is enhanced in an intense acoustic field.

Industrial application of acoustics to the CaO/HCl reaction may not be practical since the conversion enhancement in a resonant acoustic field is due to additional particle residence time in the reactor and not mass transfer improvement.

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TABLES AND FIGURES

Table 1. CaO Specific Surface Area and Mean Particle Size

Fraction Name	Distribution Range	Mass Mean Particle Size, μm	Pore Volume, ml/g	Average Pore Diameter, μm	Specific Surface Area (BET), m^2/g
Small	40μm - 2μm	3.95	1.00	0.073	14.7
Medium	110μm - 40μm	55.8	0.389	0.064	11.8
Large	150μm - 80μm	90.8	0.334	0.055	11.4

Fig. 1. EFR for Conducting Acoustically Enhanced Gas-Solid Reactions.

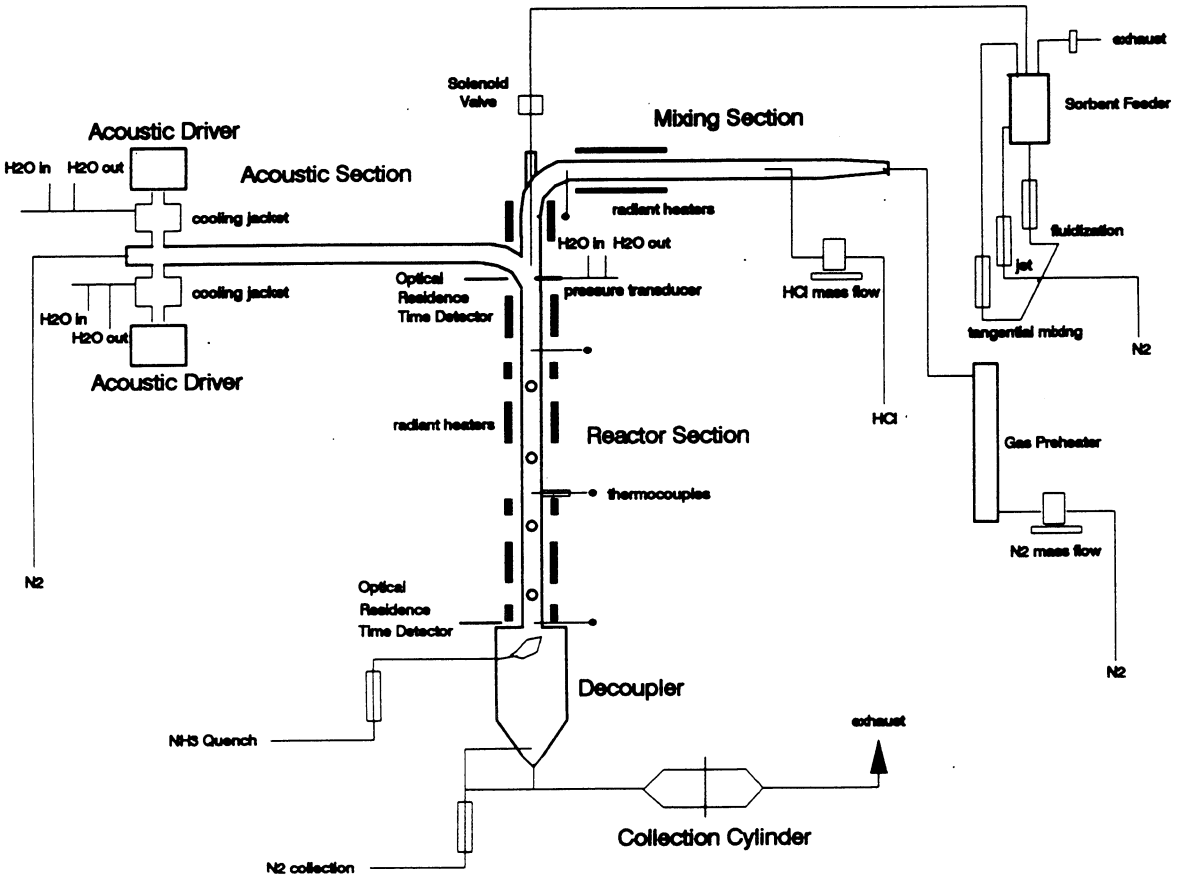

Fig. 2. Reaction Conversion With Respect to Sorbent Particle Size, No Acoustics.

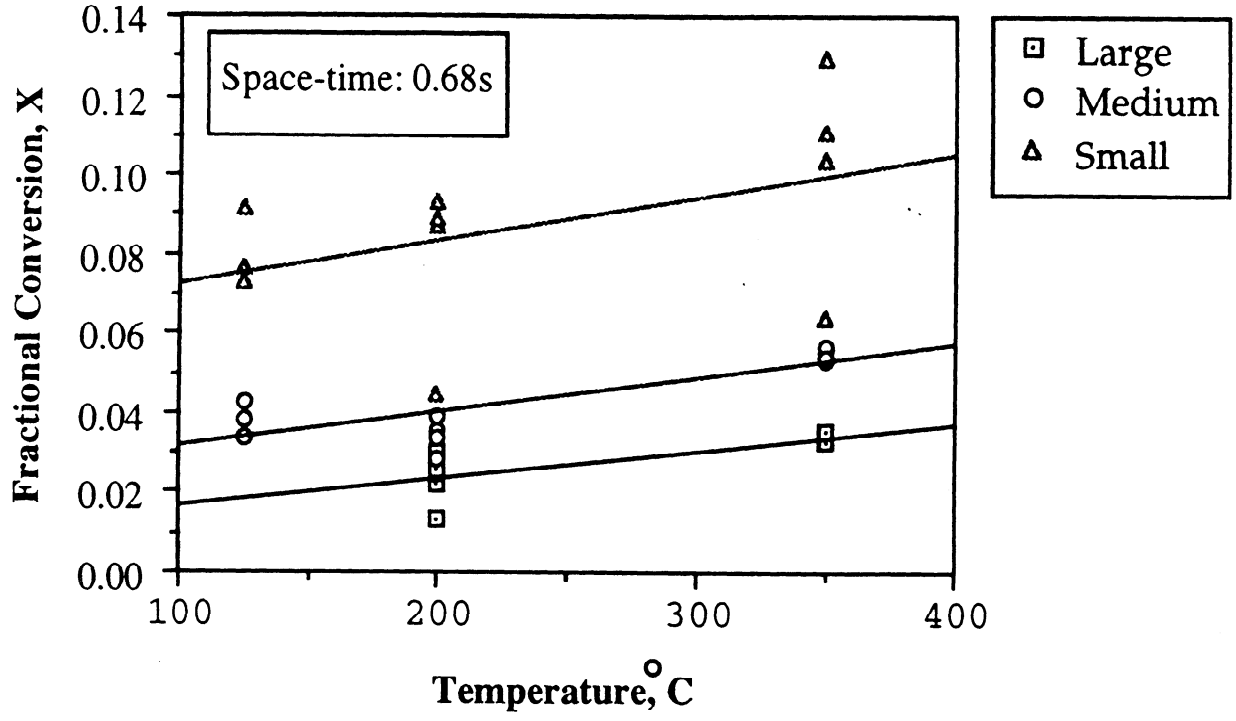

Fig. 3. Reaction Conversion for Large CaO Fraction With and Without Acoustics.

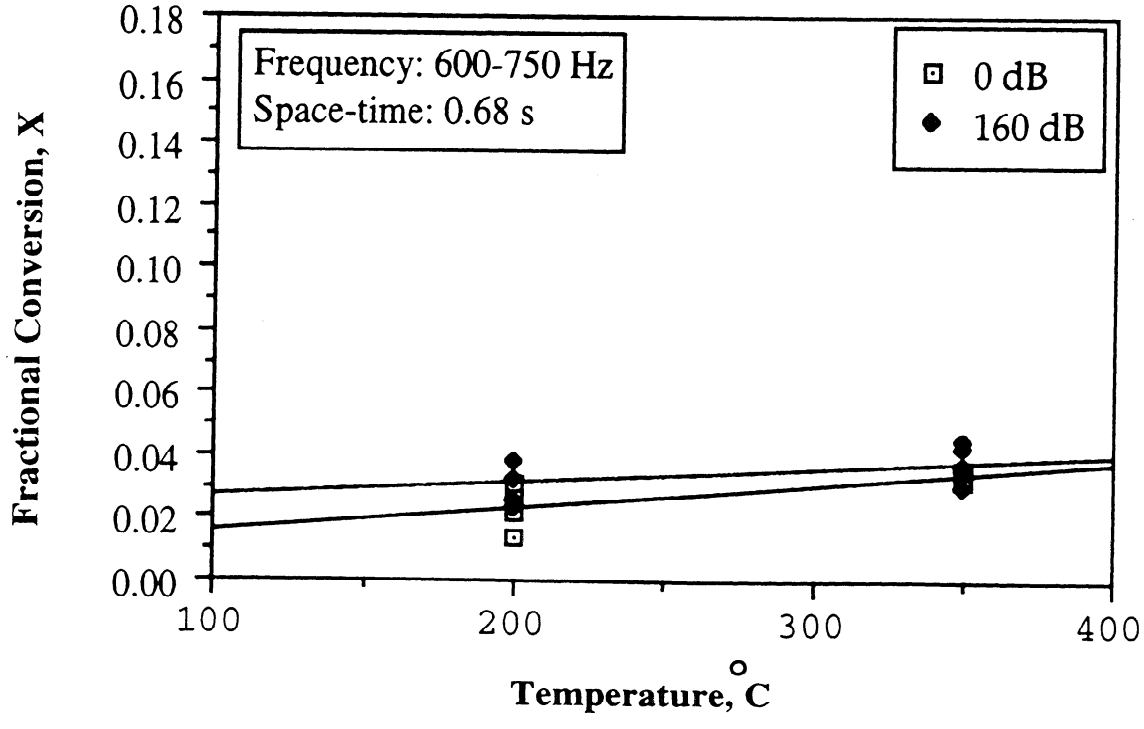

Fig. 4. Reaction Conversion for Medium CaO Fraction With and Without Acoustics.

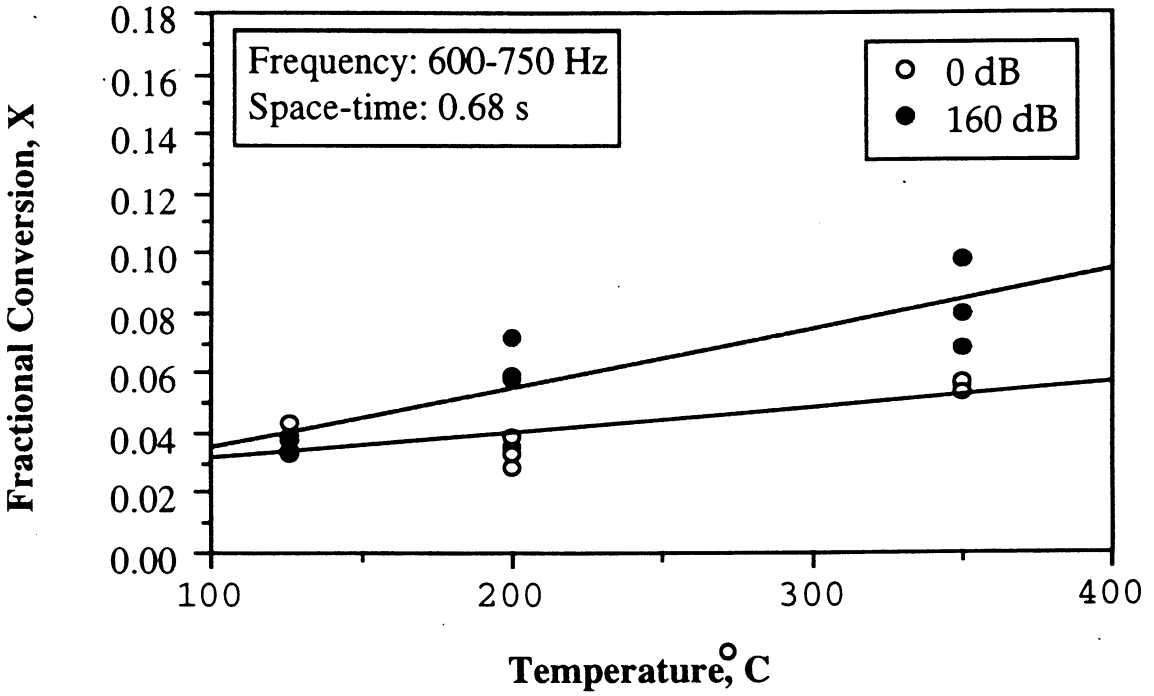

Fig. 5. Reaction Conversion for Small CaO Fraction With and Without Acoustics.

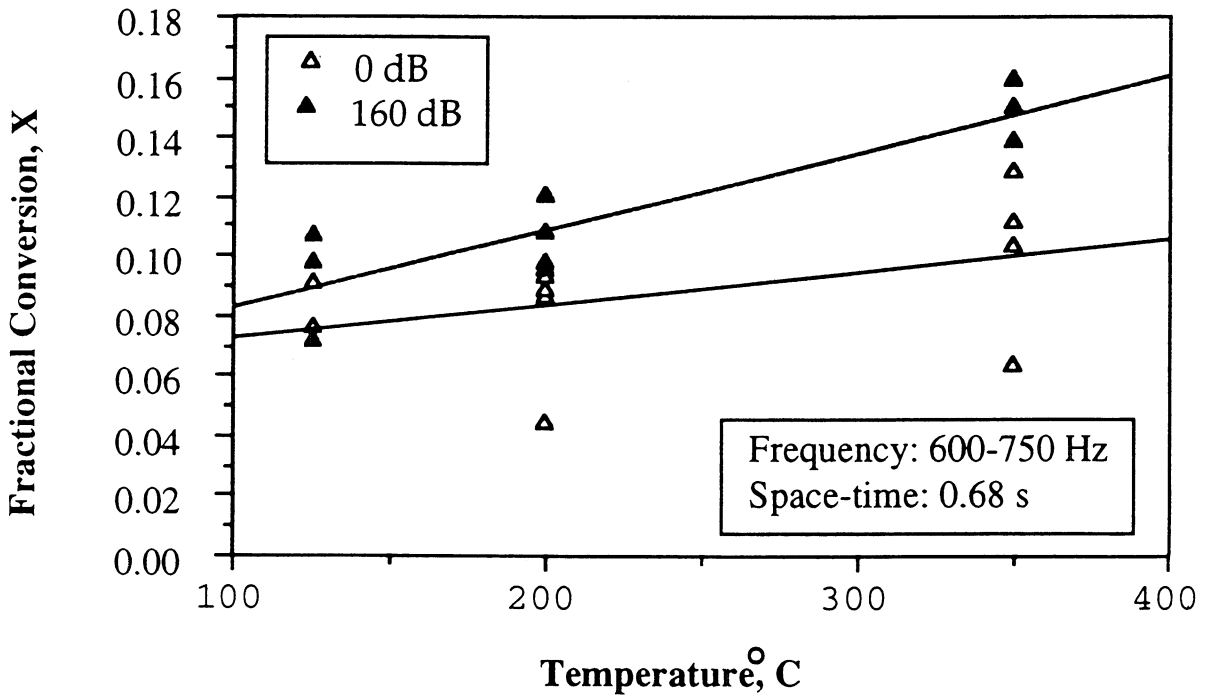

Table 2. Pore Volume Reduction of Small Fraction Sample.

Sample Name	Pore Volume, ml/g	Total Pore Area, m^2/g	Average Pore Diameter, μm
Unreacted	1.00	54.96	0.073
Reacted, (Exp.# 1896Y1)	0.6791	31.87	0.065

Fig. 6. Entrainment Factor Versus CaO Sorbent Particle Diameter.

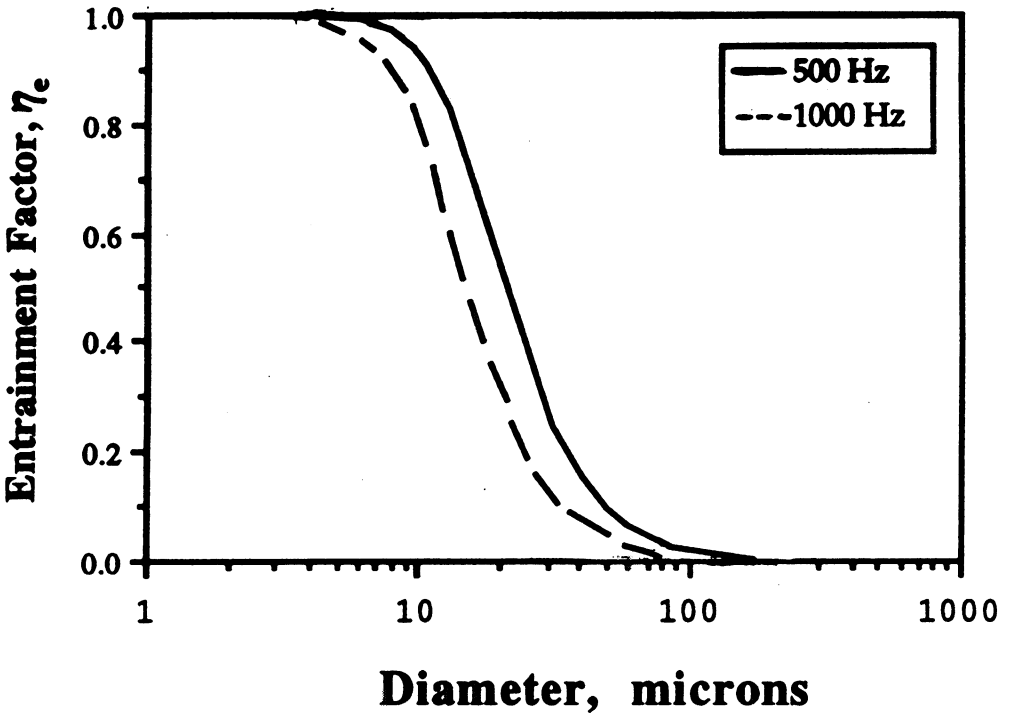

Table 3. Reaction Conversion at Various SPL.

Medium Fraction, 200 °C	
SPL, dB	X_B, %
0	3.40
145	3.43
152	3.81
163	6.29

Table 4. Turbulence Intensity.

SPL, dB	Turbulence Intensity, %
0	8
133	4
145	33
163	25

Fig. 7. Predictive Curve Comparing Kinetic Control and PLD Control.

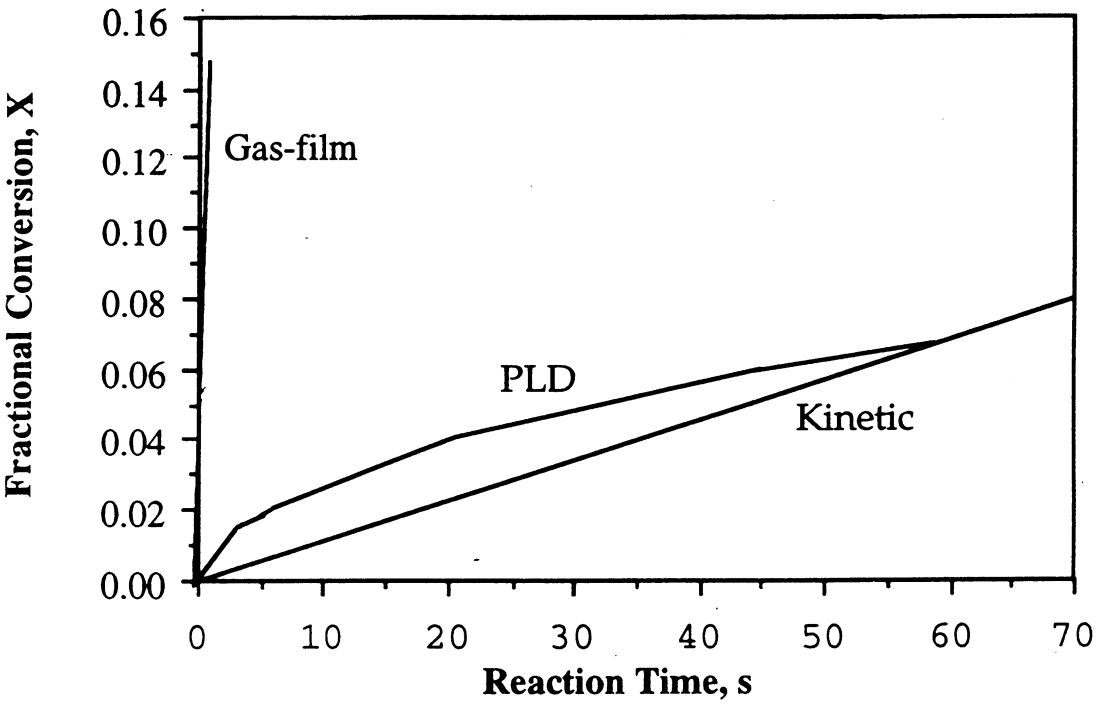

Table 5. CaO Conversion for Two Different Reactor Lengths.

Reactor Length,m	1.07		1.37	
SPL, dB	0 dB	160 dB	0 dB	160 dB
Space-Time, s	0.53	0.53	0.68	0.68
X_{CaO}	2.3	3.9	3.4	6.3
Particle Residence Time,s	0.70	1.3	0.85	1.4

Fig. 8. CaO Conversion Versus Estimated Particle Residence Time With and Without Acoustics.